

THIS REPORT HAS BEEN DELIMITED
AND CLEARED FOR PUBLIC RELEASE
UNDER DOD DIRECTIVE 5200.20 AND
NO RESTRICTIONS ARE IMPOSED UPON
ITS USE AND DISCLOSURE.

DISTRIBUTION STATEMENT A

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED.

UNCLASSIFIED

D 4 5 4 5 7 7

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

CATALOGED BY UUUU

AS AD No. _____

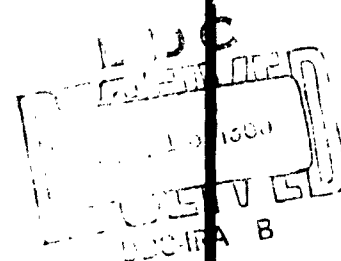
4 5 4 5 7 7

ATL-TR-64-80

THEORETICAL AND EXPERIMENTAL STUDY OF
DETONATION WAVE REINFORCEMENT AND SHAPING TECHNIQUES

December 1964

Directorate of Armament Development
Det 4, Research and Technology Division
Air Force Systems Command
Eglin Air Force Base, Florida



Qualified requesters may obtain copies from DDC. Orders will be expedited if placed through the librarian or other person designated to request documents from DDC.

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related government procurement operation, the government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Do not return this copy. Retain or destroy.


**THEORETICAL AND EXPERIMENTAL STUDY OF
DETONATION WAVE REINFORCEMENT AND SHAPING TECHNIQUES**

FOREWORD

This theoretical investigation of shaped charge design was conducted under Air Force Contract No. AF 08(635)-3624 between 1 May 1963 and 31 August 1964 by Hayes International Corporation, Birmingham, Alabama. The report details the development of a shaped charge design, its manufacture, and initial tests at Eglin Air Force Base, Florida.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.


for CHARLES E WOOD
Major, USAF
Chief, Ballistics Division

CONTENTS

	<u>Page.</u>
FOREWORD	11
LIST OF ILLUSTRATIONS	1v
SUMMARY	1
INTRODUCTION	2
THEORETICAL DEVELOPMENT OF SHAPED CHARGE PROJECTOR.	3
DISCUSSION OF THEORETICAL DEVELOPMENT.	17
FABRICATION AND TESTING OF SHAPED CHARGE	19
CONCLUSIONS	24
BIBLIOGRAPHY.	25
DISTRIBUTION	26

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Baum's Shaped Charge	3
2	Collapse of Liner	5
3	Shaped Charge with Wave Shaping Lens	6
4	Experimental Arrangement for Measuring Elapsed Time	7
5	Transmission Times and Velocity Curve Through Polypropylene	9
6	Details of Liner Collapse.	13
7	Critical Collapse Angle for Aluminum.	16
8	Assembly Drawing of Shaped Charge	20
9	Schematic View of Testing Arrangement	21
10	Sequence of Photographs from Kerr Cell Camera	23

SUMMARY

A study has been performed to determine the design criteria for a shaped charge and the associated liner geometry, employing wave shaping techniques. Heretofore, shaped charge jets have been characterized by a velocity gradient along the jet. The objective of this study was to design a shaped charge which would produce a jet characterized by a uniform velocity. Such a jet would be projected downrange essentially as a single particle rather than a spray of fine particles. Parametric equations for a wave shaping lens were solved by an internally-programmed digital computer. The proposed shaped charge design, featuring a cylindrical, metallic liner and a wave shaping lens of Polypropylene plastic, was fabricated and test firings were accomplished.

I. INTRODUCTION

In the years since World War II a considerable amount of work has been devoted to studies of high speed jet formation, collision of jets, and hypervelocity particle projection. This work has been stimulated in recent years by the need to simulate meteoric impacts, which can affect the performance of ballistic missiles, satellites, and other space vehicles. The velocities of meteors vary from 11.2 km/sec to 72 km/sec. The highest velocity for discrete particles reported in the literature of terminal ballistics is about 10 km/sec. However, scientists at Ballistics Research Laboratory have developed a type of shaped charge theoretically capable of accelerating a beryllium pellet to a speed of 21 km/sec. Although such a velocity would represent a considerable improvement over the highest reported velocity, it would still be well below the maximum velocity attributed to meteors. Accordingly, this study was undertaken to review the work done in the field of hypervelocity projection and to derive a practical design for a shaped charge capable of projecting a suitable mass at as high a velocity as possible.

The establishment of this design has encompassed studies of liner geometry and jet formation, detonation wave reinforcement, wave shaping techniques, shock wave propagation, and detonation characteristics of secondary high explosives.

The book, Explosion Physics, by Baum, Stanyukovich, and Shekhter¹ was found to give the most valuable information on which to base an analysis. The more important chapters treat "Elementary Shock Wave Theory", "Theory of Detonation Waves", and "Cumulation"; the last chapter includes discussions of (a) the active part of a shaped charge, (b) the theory of converging jets, (c) cumulation theory in the presence of a metallic liner, (d) motion of a cumulative jet, and (e) super-speed cumulation.

Shaped charges manufactured in accordance with the results of this study have been test-fired at Eglin Air Force Base, Florida.

II. THEORETICAL DEVELOPMENT OF SHAPED CHARGE PROJECTOR EXPOSITION OF BAUM'S SHAPED CHARGE PROJECTOR

The pertinent portions of Baum's book were thoroughly reviewed, and the derivations of those equations relating to shaped charges were verified. The significant feature of Baum's treatment of shaped charges is the geometry of the lens. He uses a massive lens to channel the detonation wave around the end of a cylindrical liner and to introduce the wave from the side (See Fig. 1). The detonation wave, turned by the lens, propagates from y_0 to x_0 , with the wave front

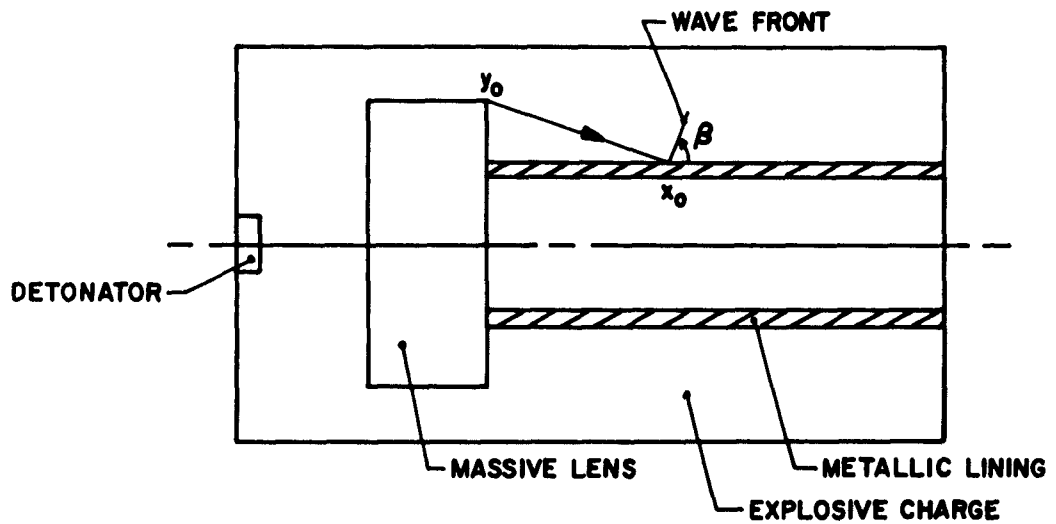


Figure 1. Baum's Shaped Charge.

making an angle β relative to the liner. The angle β increases as the wave front moves along the length of the liner. The pressure P_0 exerted on an element of liner decreases with increasing β according to the equation

$$P_0 = P_i \left[1 + \frac{17}{27} \cos^2 \beta \right], \quad (1)$$

where P_1 is the unconfined explosion pressure.

Assuming that an element of liner moves normally to the charge axis, the differential equation describing its motion is

$$\frac{d^2 y}{dt^2} = \frac{P}{\delta \lambda} \quad (2)$$

δ being the liner density and λ , the liner thickness. Substituting for the pressure P the expression

$$P = P_0 \left(\frac{t_0 - t_1}{t - t_1} \right)^3, \quad (3)$$

derived from thermodynamic considerations, with t_0 and t_1 denoting times required for the detonation wave to propagate from y_0 to x_0 and to the boundary of the active charge respectively, and integrating Eq. 2 yields the "slam" velocity (the velocity at which the liner element approaches the charge axis),

$$W_0 = \frac{P_0}{2 \delta \lambda} (t_0 - t_1)^3 \left[\frac{1}{(t_0 - t_1)^2} - \frac{1}{(t - t_1)^2} \right]. \quad (4)$$

The basic equation of cumulation relates the slam velocity to the jet velocity W_1 :

$$W_1 = \frac{W_0}{\tan \frac{\alpha}{2}} \quad (5)$$

where α is the angle formed by the intersection of the envelope of the collapsing liner at some time t and the charge axis (see Fig. 2).

Substituting Eq. 1 into Eq. 4 reveals that the slam velocity will decrease with increasing β , as will the jet velocity in turn. Furthermore, the jet velocity, from Eq. 5, will decrease with increasing α as point x_0 moves toward the end of the liner. The result of this development is that W_1 is nonuniform, having its maximum value deep within the liner cavity. For completeness, it should be pointed out that the mass of an element of jet m_1 is related to α by the expression

$$m_1 = m_0 \sin^2 \frac{\alpha}{2} ,$$

where m_0 is the mass of an element of liner, so that for a jet of specific mass, α has a lower bound. Furthermore, Eq. 5 is found experimentally to break down at very small α , again placing a lower bound on α .²

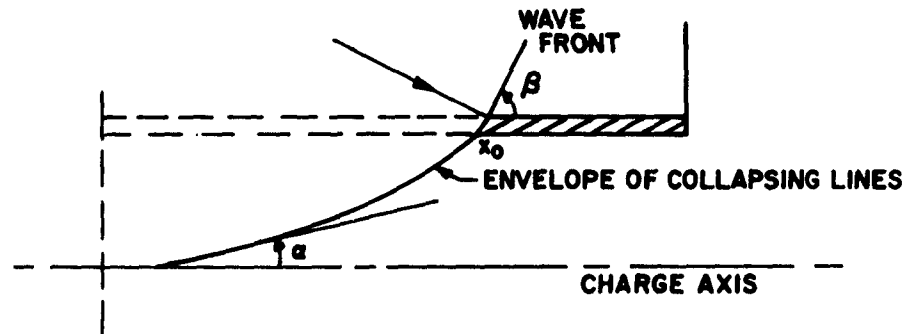


Figure 2. Collapse of Liner.

INCORPORATION OF WAVE SHAPING LENS IN SHAPED CHARGE PROJECTOR

The design goal of this study was a shaped charge characterized by a constant velocity jet with a total jet mass of one gram. The constant velocity characteristic should keep the jet concentrated and prevent breakup. To achieve this characteristic the detonation wave must impinge on the liner almost simultaneously along its length, the actual value of β being determined by the desired value of α ($\geq \alpha_c$ the critical angle for jet formation). Introducing a wave shaping lens of the proper geometry and material can effect just such a refraction as may be dictated (see Fig. 3). The treatment for this case is essentially Baum's, although modified to take into consideration the wave shaping lens.

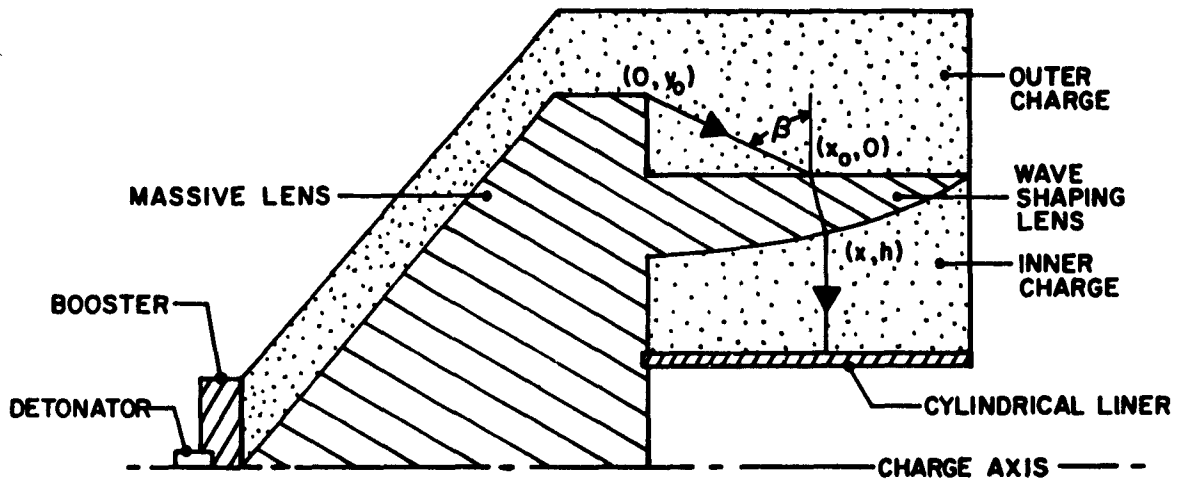


Figure 3. Shaped Charge with Wave Shaping Lens.

The massive lens serves to channel the detonation wave away from the end of the liner and to prevent a shock wave from reaching the liner before the detonation wave can collapse the liner and form the jet. The detonation wave, turned by the massive lens as before, propagates from y_0 to x_0 in a time t_0 given by

$$t_0 = \frac{\sqrt{x_0^2 + y_0^2}}{D} \quad , \quad (6)$$

D being the detonation wave velocity in the explosive, and impinges on the lens at an angle β . Assuming that the shock wave induced in the lens material travels across the lens by the shortest geometrical distance (i.e., along the perpendicular to the inner surface which passes through x_0) and that the inner surface is described by $h = h(x)$, the distance traveled S_1 is

$$S_1 = h \sqrt{\left(\frac{dh}{dx}\right)^2 + 1} \quad (7)$$

where the derivative $\frac{dh}{dx}$ is the slope of the tangent to the inner surface at x . The shock velocity through the lens material is not constant, so the elapsed time for the shock to traverse the lens and detonate the inner charge must be determined experimentally. This elapsed time is dependent on the explosive-material combination, the angle β at which the detonation wave strikes the material, the detonation shock strength, the variation in the induced shock with variable β , and the thickness of the material.

EXPERIMENTAL STUDIES OF LENS DELAY TIME

A series of experiments was undertaken at Eglin Air Force Base in October 1963 to choose the optimum lens material and to measure the total elapsed time for shock propagation through the material as a function of material thickness. Figure 4 shows schematically the experimental arrangement. The explosive used was pressed tetryl pellets, $\frac{1}{2}$ inch by $\frac{1}{2}$ inch, having a density of about 1.5 gm/cm^3 .

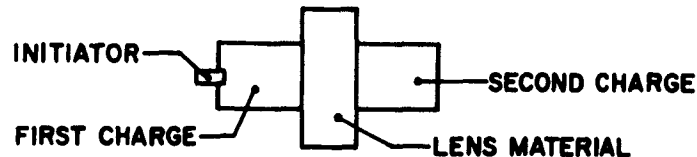


Figure 4. Experimental Arrangement for Measuring Elapsed Time.

Lens materials tested were Lexan and Polypropylene. A B&W 189 framing camera was used to photograph the progression of the detonation wave through the tetryl pellets and to measure the total delay time for shock propagation through the test material and initiation of detonation in the second charge. The camera was operated as close to 2.4×10^6 frames per second as possible, with a corresponding interframe time of .42 microsecond. Data was reduced at Hayes by employing optical scaling factors and the interframe time.

Stimulation of detonation in the second charge is accomplished by the shock wave which passes through the inert lens material. The initial parameters of the shock wave in the lens are determined by the characteristics of the first charge and of the medium. The shock wave weakens as it propagates through the inert material, gradually approaching the sonic velocity. The shock wave may or may not stimulate detonation in the second charge. Whether or not detonation occurs depends on the strength of the shock wave at the site of encounter with the second charge. When detonation does occur, a certain delay time is experienced before a detonation wave is established in the second charge. This delay time for the deflagration-to-detonation transition depends on the detonation characteristics of the charge and the strength of the stimulating shock. For the present analysis the lens delay time was assumed to be inversely proportional to the shock strength.

The experiments resulted in the selection of Polypropylene and verified that detonation does not occur when the thickness exceeds some critical value. A graph of elapsed time vs. material thickness, along with a plot of the variation of average velocity with thickness, is shown in Fig. 5. The elapsed time vs. material thickness data were fitted empirically to a quadratic equation (Eq. 8),

$$t_1 = 2.283 S_1^2 + 0.9252 S_1 + 0.2714, \quad (8)$$

where the numerical coefficients have suitable dimensions. The velocity curve was taken from the reciprocal of dt_e/ds :

$$v = [4.566 S_1 + 0.9252]^{-1}.$$

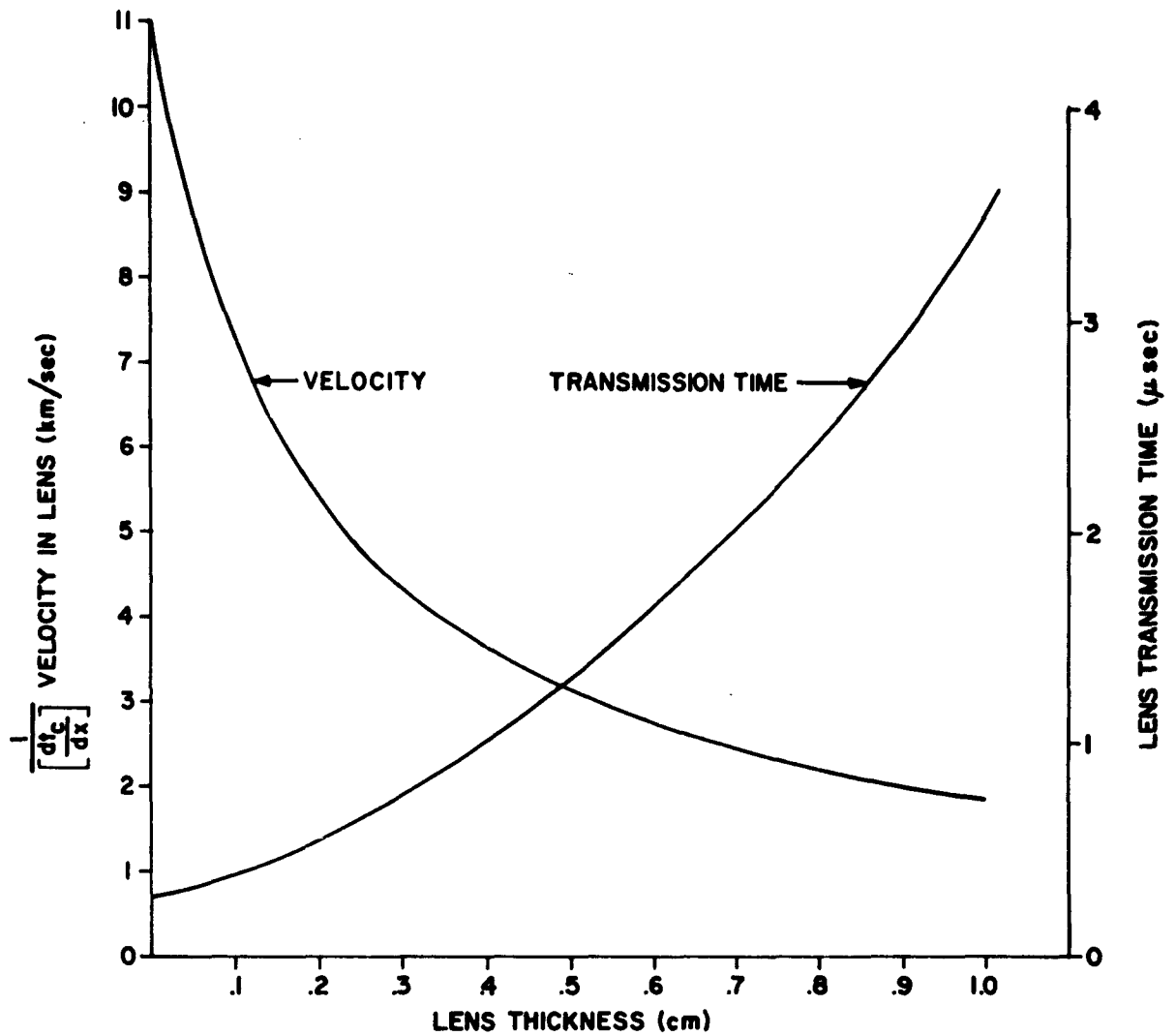


Figure 5. Transmission Times and Velocity Curve Through Polypropylene.

DEVELOPMENT OF PARAMETRIC EQUATIONS FOR SHAPED CHARGE PROJECTOR

The interface pressure P_0 varies with β , the angle at which the detonation wave strikes the lens, according to

$$P_0 = P_1 \left[1 + \frac{17}{27} \cos^2 \beta \right], \quad (9)$$

where P_i is the unconfined explosion pressure. From Fig. 3, the term $\cos^2 \beta$ can be written $y_o^2 / (x_o^2 + y_o^2)$. Substituting this expression in Eq. 9, we have

$$P_o = P_i \left[\frac{64 y_o^2 + 27 x_o^2}{27 (x_o^2 + y_o^2)} \right]$$

which can be written as

$$P_o = \frac{64}{27} \frac{\phi_2}{\phi_1} P_i \quad (10)$$

where

$$\phi_2 = \frac{27}{64} x_o^2 + y_o^2 \quad \text{and} \quad \phi_1 = x_o^2 + y_o^2 .$$

Baum states that the interface pressure for normal reflection is related to the explosion pressure by

$$P_o = \frac{64}{27} P_i \quad (11)$$

and the explosion pressure is given by

$$P_i = \frac{\rho_c D^2}{4} , \quad (12)$$

ρ_c being the density of the charge.

Comparing Eq. 11 with Eq. 10, we see that the ratio ϕ_2 / ϕ_1 is the compensating term for variation of interface pressure with the angle of obliquity. Since Eq. 8 was determined for the case of normal shock incidence on the lens material, it must be modified to include the dependence on β . This dependence is incorporated through the inverse ratio ϕ_1 / ϕ_2 as

$$t_1 = \frac{\phi_1}{\phi_2} \quad 2.283 S_1^2 + .9152 S_1 + .2714 . \quad (13)$$

From thermodynamic considerations, the pressure on an element of liner can be written as

$$P = \frac{8}{27} P_i \left(\frac{S_2}{T_2 D} \right)^3, \quad (14)$$

where S_2 is the thickness of the charge between the lens and the liner (a quantity varying with x) and T_2 is a temporal parameter commencing when the detonation wave crosses the boundary between the active and passive charges. If this boundary is assumed to lie halfway between the inner surface of the lens and the liner, if the time for wave propagation to the liner is called t_3 , and if the time to the active-passive boundary is called t_2 , then the following relations can be established:

$$\left. \begin{aligned} D(t_3 - t_2) &= \frac{S_2}{2} \\ T_2 &= (t - t_2). \end{aligned} \right\} \quad (15)$$

Substituting Eqs. 15 and 11 into Eq. 14 yields

$$P = P_o \left(\frac{t_3 - t_2}{t - t_2} \right)^3, \quad (16)$$

which is the same relation given as Eq. 3. The time variables t_3 and t_2 are given by

$$\begin{aligned} t_3 &= \frac{\sqrt{\phi_1}}{D} + t_1 + \frac{S_2}{D}, \text{ and} \\ t_2 &= t_3 - \frac{S_2}{2D}. \end{aligned} \quad (17)$$

At the time t_3 , when the detonation wave reaches the liner element, the element of liner commences to move toward the charge axis, so that the law of motion of an element is determined by the expression,

$$m \frac{d^2 y}{dt^2} = PA$$

where y is measured from an axis coinciding with an exterior element of the liner, and A is the area of the element of liner. If λ is the thickness and ρ the density of the liner, then

$$\frac{d^2 y}{d t^2} = \frac{P}{\rho \lambda} \quad (18)$$

Integrating Eq. 18 with respect to time yields the velocity W_0 at which the element of liner approaches the charge axis:

$$W_0 = \frac{dy}{dt} = \frac{1}{\rho \lambda} \int_{t_3}^t P dt$$

$$W_0 = \frac{P_0}{2 \rho \lambda} (t_3 - t_2)^3 \left[\frac{1}{(t_3 - t_2)^2} - \frac{1}{(t - t_2)^2} \right]$$

By using the relationships expressed in Eqs. 11, 12, and 15 and by making the following substitutions

$$T_3 = t - t_3 \quad \text{and} \quad T_2 = t - t_2 ,$$

the expression for the slam velocity W_0 can be simplified to

$$W_0 = \frac{\rho_c S_2^3}{27 \rho \lambda D} \left[\frac{4D^2}{S_2^2} - \frac{1}{T_2^2} \right] \quad (19)$$

An expression for the displacement of the liner element is obtained by integrating Eq. 19 with respect to time:

$$y = \frac{4 \rho_c S_2 D}{27 \rho \lambda} \left[\frac{T_3^2}{T_2} \right] \quad (20)$$

A little manipulation of these expressions is necessary to obtain a manageable equation describing the proper lens shape for a given set of conditions imposed on the shaped charge.

There occurs in Eq. 5 the term $\tan \frac{\alpha}{2}$. For small α ,

$$\tan \frac{\alpha}{2} \approx \frac{1}{2} \tan \alpha .$$

According to Fig. 2, α is the angle between the charge axis and the tangent to the envelope of the collapsing liner at the axis, hence the tangent of α is equal to the derivative of y with respect to x at some instant in time. Differentiating Eq. 20 with respect to x gives

$$\left(\frac{dy}{dx}\right)_t = \frac{4 \rho_c D S_2}{27 \rho} \left(\frac{T_3}{T_2}\right) \left[\frac{T_3}{S_2} \frac{dS_2}{dx} + \frac{T_3}{T_2} \frac{dt_2}{dx} - 2 \frac{dt_2}{dx} \right].$$

Substituting this expression and Eq. 19 into Eq. 5 gives the following expression for W_1 in terms of the parameters of the shaped charge:

$$W_1 = \frac{S_2^2 \left[\frac{4D^2}{S_2^2} - \frac{1}{T_2^2} \right]}{\frac{2D^2 T_3}{T_2} \left[\frac{T_3}{S_2} \frac{dS_2}{dx} + \frac{T_3}{T_2} \frac{dt_2}{dx} - 2 \frac{dt_2}{dx} \right]} \quad (21)$$

From Fig. 6, it is evident that some point x_1 the sum of the thickness of the inner charge S_2 and the thickness of the lens h is a constant.

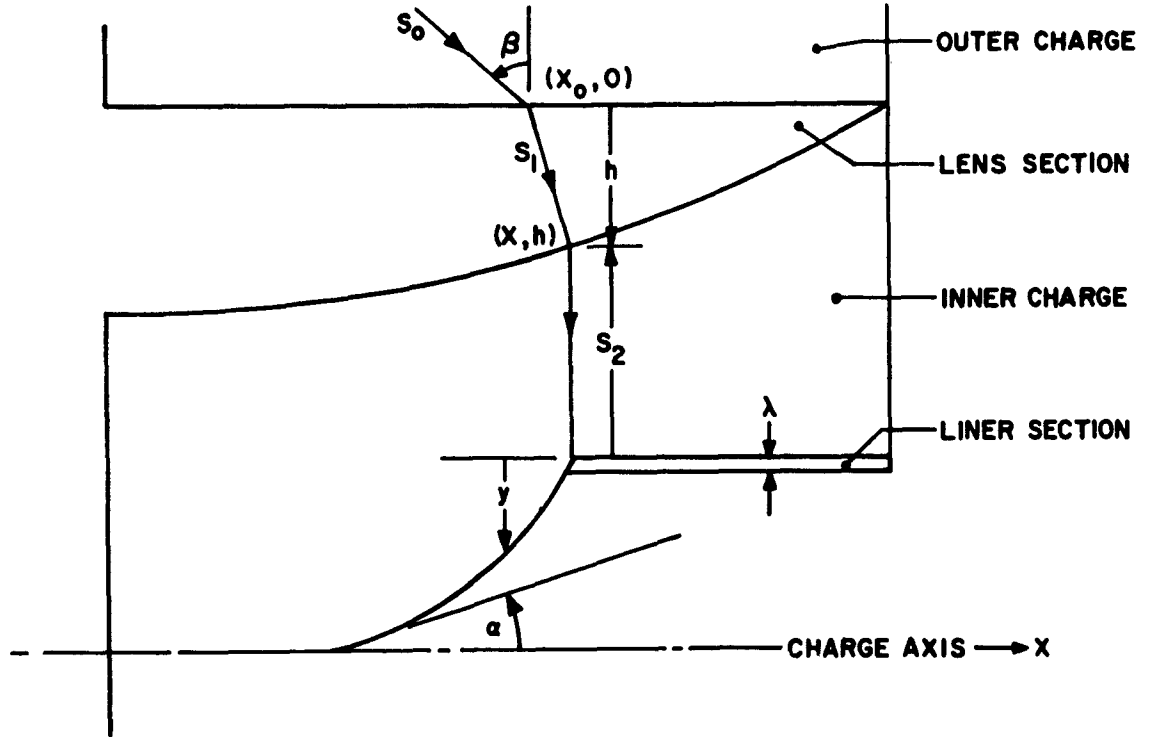


Figure 6. Details of Liner Collapse.

Hence, their derivatives are related by

$$\frac{dh}{dx} = -\frac{dS_2}{dx}.$$

Utilizing this relationship and the derivatives with respect to x of Eqs. 17, Eq. 21 can be written as

$$W_1 = \frac{S_2^2 \left[\frac{4D^2}{S_2^2} - \frac{1}{T_2^2} \right]}{\frac{2D^2 T_3}{T_2^2} \left\{ (T_3 - 2T_2) \frac{x_0}{D\sqrt{\phi_1}} \frac{dx_0}{dx} + (T_3 - 2T_2) \frac{dt_1}{dx} - \left[\left(\frac{T_3}{2} - 2T_2 \right) \frac{1}{D} + \frac{T_2 T_3}{S_2} \right] \frac{dh}{dx} \right\}}. \quad (22)$$

DEVELOPMENT OF AUTOMATED COMPUTATIONAL TECHNIQUES

The development of a digital computer program for determining the proper lens shape requires an equation in $\frac{dh}{dx}$ which can be solved numerically for $\frac{dh}{dx}$. In addition to the explicit term in $\frac{dh}{dx}$, Eq. 22 contains $\frac{dh}{dx}$ implicitly in the terms x_0 , dx_0/dx , dt_1/dx , and $\sqrt{\phi_1}$. Substitutions for the first three quantities must be made before solving Eq. 22 for the lens shape parameter $\frac{dh}{dx}$. These substitutions are:

$$x_0 = x + h \left(\frac{dh}{dx} \right)$$

$$\frac{dx_0}{dx} = 1 + h \frac{d^2 h}{dx^2} + \left(\frac{dh}{dx} \right)^2$$

$$\frac{dt_1}{dx} = \frac{\phi_1}{\phi_2} \left[4.566 S_1 + .9152 \right] \frac{dS_1}{dx} + \left[2.283 S_1^2 + .9152 S_1 + .2714 \right] \frac{d}{dx} \left(\frac{\phi_1}{\phi_2} \right).$$

In the third substitution,

$$\frac{\phi_1}{\phi_2} = \frac{x_0^2 + y_0^2}{\frac{77}{64} x_0^2 + y_0^2}$$

$$\frac{dS_1}{dx} = \frac{h}{S_1} \left(\frac{dh}{dx} \right) \left(1 + h \frac{d^2 h}{dx^2} + \left(\frac{dh}{dx} \right)^2 \right)$$

$$\frac{d}{dx} \left(\frac{\phi_1}{\phi_2} \right) = \frac{37 x_0 y_0^2}{32 \phi_2^2} \frac{dx_0}{dx}.$$

Equation 22 can now be written as a power series in $\frac{dh}{dx}$ as follows:

$$A \left(\frac{dh}{dx} \right)^3 + B \left(\frac{dh}{dx} \right)^2 + C \left(\frac{dh}{dx} \right) + D = 0, \quad (23)$$

where the coefficients are

$$A = h \left[\frac{\phi_2^2}{D \sqrt{\phi_1}} + \frac{37}{32} y_0^2 (K_2 S_1^2 + K_1 S_1 + K_0) + \frac{\phi_1 \phi_2}{S_1} (2K_2 S_1 + K_1) \right]$$

$$B = x \left[\frac{\phi_2^2}{D \sqrt{\phi_1}} + \frac{37}{32} y_0^2 (K_2 S_1^2 + K_1 S_1 + K_0) \right]$$

$$C = h \left(1 + h \frac{d^2 h}{dx^2} \right) \left[\frac{\phi_2^2}{D \sqrt{\phi_1}} + \frac{37}{32} y_0^2 (K_2 S_1^2 + K_0) + \frac{\phi_1 \phi_2}{S_1} (2K_2 S_1 + K_1) \right] -$$

$$\frac{T_3 - 4T_2}{T_3 - 2T_2} \left(\frac{\phi_2^2}{2D} \right) - \frac{T_2 T_3}{T_3 - 2T_2} \left(\frac{\phi_2^2}{S_2} \right)$$

$$D = x \left(1 + h \frac{d^2 h}{dx^2} \right) \left[\frac{\phi_2^2}{D \sqrt{\phi_1}} + \frac{37}{32} y_0^2 (K_2 S_1^2 + K_1 S_1 + K_0) \right] - \frac{2\phi_2^2 [T_2^2 - \frac{(S_2^2)}{2D}]}{W_1 T_3 (T_3 - 2T_2)}$$

The factors ϕ_2^2 and $\phi_1 \phi_2$ also can be expressed as power series in $\frac{dh}{dx}$ as follows:

$$A' \left(\frac{dh}{dx} \right)^4 + B' \left(\frac{dh}{dx} \right)^3 + C' \left(\frac{dh}{dx} \right)^2 + D' \left(\frac{dh}{dx} \right) + E' = \phi_i \phi_j$$

where the subscripts i, j can be equal (ϕ_2^2) or different ($\phi_1 \phi_2$) and the coefficients are functions of the numerical ratio $a (= \frac{27}{4})$, h , x , and y_0 . Substituting these expressions into the coefficients of Eq. 23 and collecting terms gives a power series equation which can be solved numerically for $\frac{dh}{dx}$. The solution is determined by the Newton-Raphson method in which an approximation to the root is substituted into the equation, and an increment is calculated which improves the approximation.* This iterative process is continued until the root is approximated as closely as desired. The lens thickness h at a point for which $\frac{dh}{dx}$ has been determined can be calculated by

* If $f(x) = 0$ is the equation and $f'(x) = 0$ is the derivative, and if x_0 is an approximate solution, then an improved value of the root is given by³

$$x = x_0 + \Delta x; \Delta x = -\frac{f(x_0)}{f'(x_0)}.$$

substituting into the equation,

$$h_j = h_i + \Delta x \frac{dh}{dx} ,$$

where i and j refer to two consecutive points of calculation and Δx is the axial separation between points i and j . Other quantities such as the slam velocity can be calculated by substituting into the appropriate equations.

LIMITATIONS ON DESIGN

It was pointed out early in this report that Eq. 5 has been found experimentally to break down at small values of the collapse angle α . Walsh, et al. have shown that, given a slam velocity W_0 , α must equal or exceed some critical angle α_c in order for a jet to be formed. A graph of α_c vs. slam velocity is shown in Fig. 7.

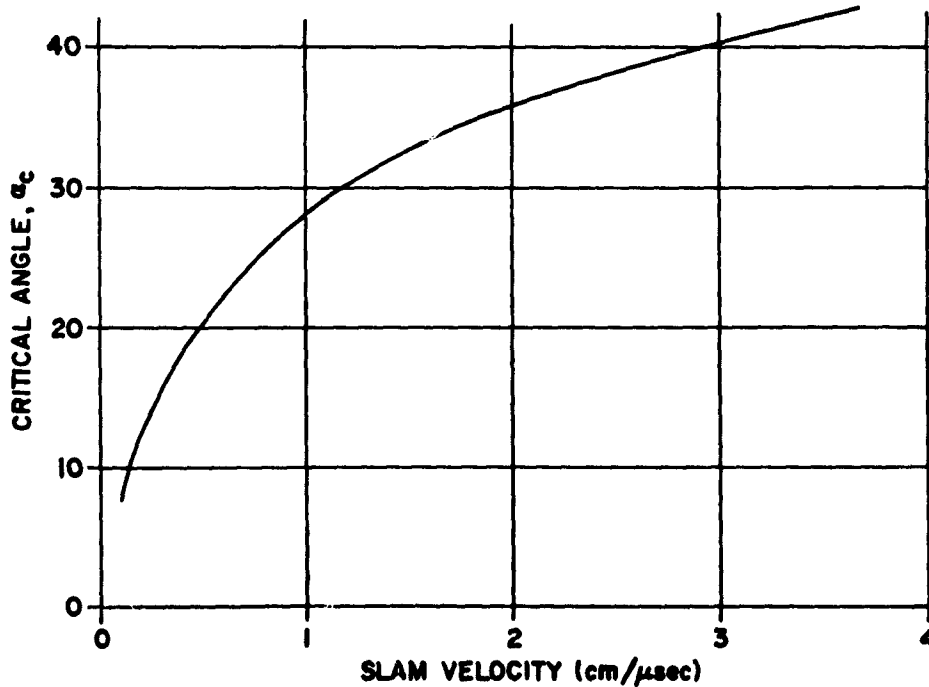


Figure 7. Critical Collapse Angle for Aluminum.

The details of the curve are dependent on the material parameters of the liner as well as the dynamics of the collapsing process.

III. DISCUSSION OF THEORETICAL DEVELOPMENT

ASSUMPTIONS INCORPORATED INTO DEVELOPMENT

During the course of developing the parametric equations for the wave shaping lens, it became evident that many pertinent points in the theory were uncertain or even unknown. In order to complete the development, it was necessary to make certain assumptions. In this section the assumptions that were incorporated into the development will be discussed, with attention to the consequences and the need for validation or correction of the assumptions.

When the booster detonates the charge behind the massive lens (see Fig. 3), the detonation wave propagates around the lens, but it also sets up a shock wave in the lens. The question must arise whether or not the shock in the lens might cause premature detonation of the forward charge. The assumption made is that detonation will not occur. This assumption is in keeping with the experiments performed at Eglin in October 1963 which demonstrated that inert material exceeding a certain thickness attenuates a shock sufficiently to prevent detonation.

At the point y_0 the detonation wave propagates into the region of the forward charge. The first assumption made is that the wave propagates with constant velocity and radially to the outer surface of the wave shaping lens. The assumption of a constant velocity, dependent only on the properties of the explosive, is valid for ideal detonation.⁴ For nonideal detonation the velocity of propagation depends on the physical state of the explosive, primarily its density and particle size, the minimum charge thickness, and the degree of confinement. Insufficient charge thickness can reduce ideal detonation to nonideal detonation or even prevent detonation altogether. Precautions were taken in designing the shaped charge to make the charge thickness at least 1 cm at all points. The second assumption made is that the explosive selected, Composition B, detonates ideally under the existing conditions. This assumption appears to have been validated by the results of the initial test firings of the shaped charge.

At the interface between the explosive and the wave shaping lens the detonation wave induces a shock in the lens. According to Baum the interface pressure is given by Eqs. 9 and 12. The first assumption made at this point in the development is that the strength of the induced shock is proportional to the interface pressure. The second

is that the induced shock travels across the lens along the shortest geometrical path passing through the point of initiation, i.e., along the perpendicular to the inner surface of the lens. This is a very serious assumption, and its validity, even approximately, is by no means obvious. If the shock propagated through the lens with a constant speed and if a Huygens' construction could be applied, such an assumption would be valid; but a shock does not propagate with a constant speed, and the applicability of a Huygens' construction is uncertain. Despite the extensive studies into the behavior of shock waves in gaseous media, the theory of shock behavior in condensed media is much less well established. The absence of such a theory necessitated assumptions on shock behavior, and the assumptions made presented fewer mathematical complications. Furthermore, the refractive behavior here attributed to shock propagation is consistent with other forms of wave motion at interfaces, but much fundamental work is needed in this area.

At the inner surface of the wave shaping lens the shock wave stimulates detonation in the inner charge. The detonation, however, is not established at the interface but at some distance into the charge, this "skip" distance depending on the strength of the shock and the properties of the explosive. The assumptions made at this point were that the "skip" distance is negligible and that the detonation of a differential volume of charge proceeds only along the normal to the charge axis. The former assumption was made in the absence of a satisfactory theory capable of specifying the "skip" distance and its associated time delay. The latter assumption was chosen because of the cylindrical symmetry of the charge and the greater mathematical tractability afforded by the assumption.

Finally, there arises the question of demarcation between the passive and active charges. When a column of explosive detonates half of the explosion products move toward each end of the column. When the column is confined, half of the products act on each confining surface. If the column is confined at one end by the lens and at the other by the liner, presumably half of the explosion products act on each surface, and the separation between passive and active charges falls across the middle of the column. Considering all the differential columns of charge leads one to draw the passive-active boundary midway between the lens and the liner. This was the argument followed in establishing the lens design, but the argument fails to consider the effect of the outer charge on the wave shaping lens. If the lens is either more or less effective as a confining surface than the liner, the separation may be shifted. The thickness of the active charge is critical, entering a number of equations in the development, some to the second or third power.

IV. FABRICATION AND TESTING OF

SHAPED CHARGE

The shaped charge projectors furnished on this contract were manufactured jointly by Hayes International Corporation and A. Lavine & Co., Palos Verdes Estates, California. The lenses and liners were made by Hayes, while the explosive was cast by A. Lavine & Co.

The wave shaping lens, made from polypropylene plastic, was machined from five-inch diameter rod stock. The liner was made from aluminum tubing $1\frac{1}{2}$ inches in diameter and .049 inch thick. The lenses and liners were then shipped to Lavine for the casting of the explosive in accordance with Hayes drawings. (See Figure 8).

The casting of the explosive was accomplished in two steps. The first step consisted of casting the detonating charge of Composition B around the lens. This was accomplished by using a three-piece external tooling device consisting of the external cone, the main barrel, and a short riser. The lens itself was used as the internal tool. The lens was positioned inside the external tooling and held in place by means of a guide pin. The explosive melt was then poured between the lens and the tooling, both of which had been heated to the temperature of the melt. The whole system was then slowly cooled to ambient temperature.

The second step consisted of casting the active charge, Composition B, and the booster, 50% PETN and 50% TNT, around the liner. A five-piece tooling device consisting of a base plate, a tapered cylinder for the active charge, a contoured cylinder for the booster charge, a cap for the liner, and a centering pin was used. The liner served as the internal tooling for the active charge casting. The active charge was cast using the base plate, tapered cylinder, liner cap, pin, and liner. When the active charge had frozen to the liner but was still hot, the tapered cylinder was replaced by the contoured cylinder, and the booster charge was cast.

These two parts were then x-rayed to ascertain that no inclusions or foreign matter existed in the charges. Those that passed the examination were cemented together and x-rayed again in three planes for final quality acceptance. After final acceptance the charges were shipped to Eglin Air Force Base for test firing.

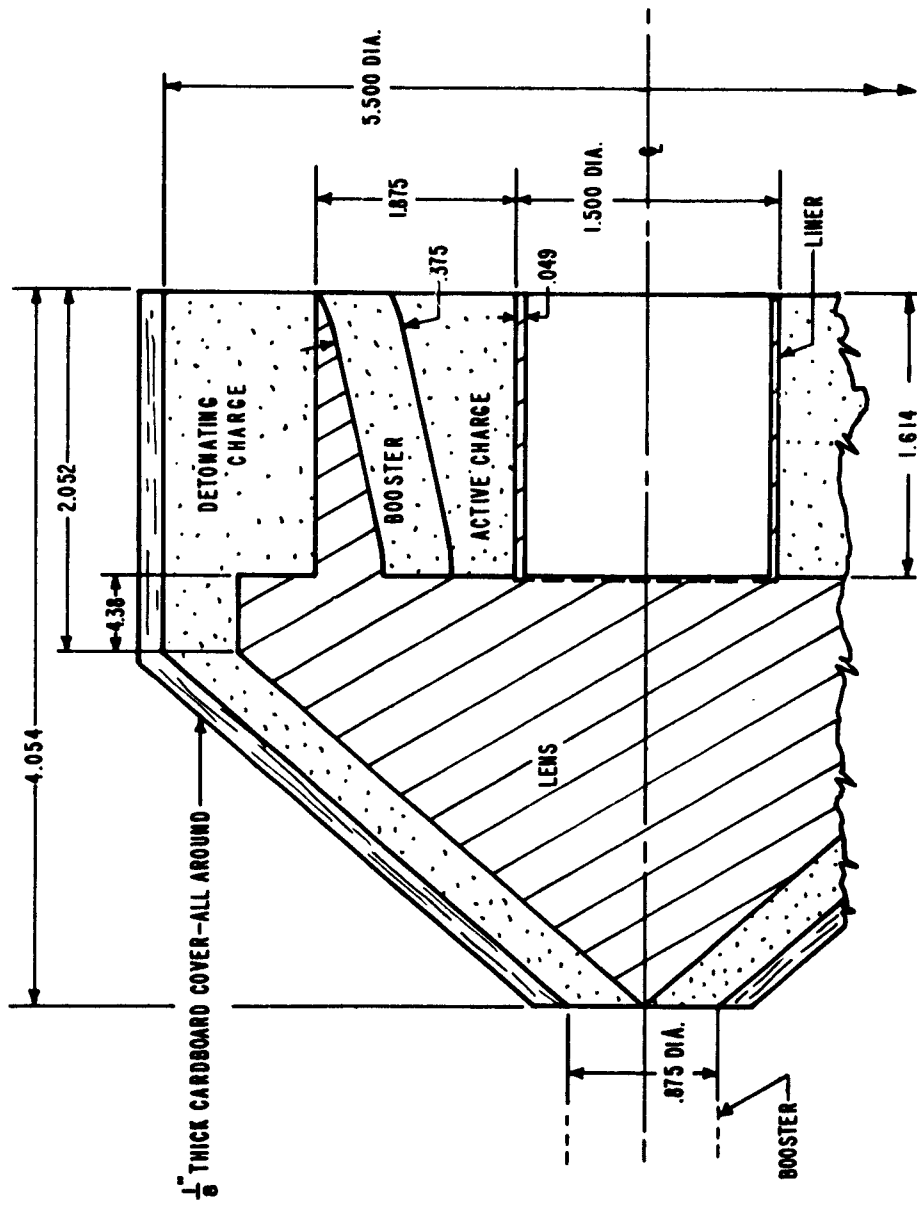


Figure 8. Assembly Drawing of Shaped Charge.

The first charges were test fired in Eglin's shaped charge range. The altitude chamber was evacuated to the equivalence of 200,000 feet and the blast chamber, to 60,000 feet. The test setup consisted of positioning the charge behind the blast shield, with a foil switch located in the altitude chamber 18 feet from the charge. Six channels of x-ray shadowgraph were used. The channels were triggered simultaneously in order to cover a velocity range from 40,000 to 80,000 feet/second.

The report from the detonation was a sharp crack as opposed to the usual boom. No particles of significant mass were detected by the x-ray plates, but the foil switch indicated that something, probably a shock wave, moved downrange at a velocity of 225,000 feet/second.

A second series of test firings consisted of three shots. The altitude chamber was evacuated to about 190,000 feet, but the blast chamber was not evacuated. Six channels of x-ray shadowgraph were triggered in parts to cover a velocity range from 40,000 to 60,000 feet/second.

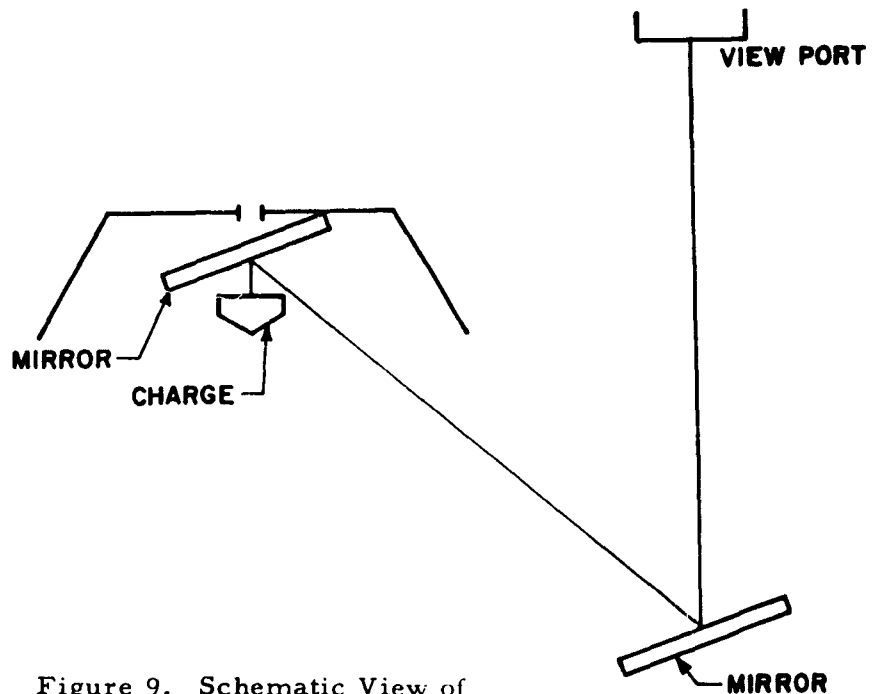
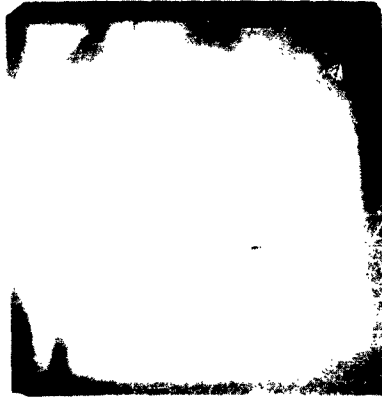


Figure 9. Schematic View of Testing Arrangement.

The report from these shots lacked the sharp crack of the previous firings, producing instead a boom that could be felt in the floor. The first shot was fired to determine whether or not a jet was formed. After firing, the target, although slightly buckled, revealed that a jet had not been formed. For the second firing a $\frac{1}{4}$ inch steel ball was positioned on the axis at the midpoint of the liner. The charge projected large fragments of the ball downrange with velocities of the order of 48,000 feet/second. A group of smaller particles was generated with velocities between 50,000 and 60,000 feet/second. The third shot of the series was photographed by means of a Kerr cell camera. Six photographs of the exploding charge were taken at intervals of 4 microseconds. The physical arrangement is shown in Fig. 9. Five of the six photographs are shown in sequence in Fig. 10. (The second photograph was faulty). The most striking feature of the sequence is that the entire face of the charge is intact after 24 microseconds, although the back portion of the charge appears to have been blown away by 20 microseconds after initiation.

(1)



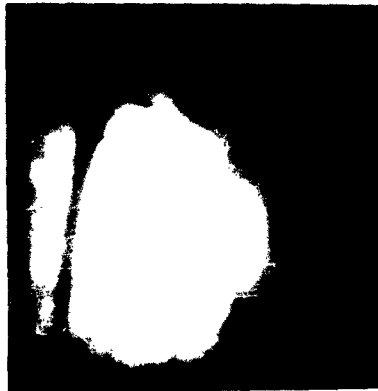
(4)



(5)



(3)



(6)



Figure 10. Sequence of Photographs from Kerr Cell Camera.

V. CONCLUSIONS

The failure of this particular shaped charge design to form a jet could be attributed to one or more of several possible causes: (1) the detonation-induced shock in the massive lens may destroy the liner before the shaped detonation wave reaches it; (2) the detonation wave may destroy the wave shaping lens prematurely; (3) the detonation wave may be too strong and vaporize the aluminum liner before the jet can be formed; or (4) the detonation wave is approaching the liner at too shallow an angle and thereby preventing the formation of a jet. The solution to the problem lies in further research, either in refinement of shock theory or trial lens shapes and liner geometries. The test shots, however, produced an extremely fast shock front downrange and demonstrated that particles suspended in the cavity could be accelerated to significant velocities.

BIBLIOGRAPHY

1. Baum, F. A., Stanyukovich, K. P., Shekhter, B. I., Fizika Vzryva (Explosion Physics), Fizmatgiz, Moscow, USSR, 1959.
2. Walsh, J. M., Shreffler, R. C., Willig, F. J., "Limiting Conditions for Jet Formation in High Velocity Collisions", Journal of Applied Physics, Volume 24, Number 3, March 1953, pp. 349 - 359.
3. Margenau, H., Murphy, G. M., The Mathematics of Physics and Chemistry, Second Edition, D. Van Nostrand Company, Inc., Princeton, N. J., 1956, p. 492.
4. Cook, M. A., The Science of High Explosives, Reinhold Publishing Corporation, New York, 1958, p. 48.

INITIAL DISTRIBUTION

1 DOD (DIAAP-1K2)	1 Univ of Chicago (Lib)
1 Hq USAF (AFTAC)	2 Franklin Institute of
1 Hq USAF (AFCIN-3K2)	the State of Penn
2 Hq USAF (AFRDC)	2 SSD (SSTRG/LC W Levin)
1 Hq USAF (AFRAE-E, L/C Hicks)	1 Calif Inst of Tech, Jet
1 Hq USAF (AFTST-EL/CS, Maj Myers)	Propulsion Lab
1 USAF (AFRST-PM/ME, Maj Geiseman)	2 John Hopkins Univ
1 Hq USAF (AFXPDK-NI)	(Applied Rsch Lab)
1 AFSC (SCRWA)	1 OAR (RROSA/Maj Davis)
1 AFSC (SCTA, Mr R Fiek)	1 OAR (RROSA/Maj Stalk)
2 BSD (Col Brassfield)	20 DDC
1 ASD (SEPRR)	3 Lewis Rsch Ctr
1 AFFDL (FDTS) Mr Parmley	2 Dir, IDA/WPNS Sys Eval Gp
2 ASD (ASAD-Lib)	1 Dir, USAF PROJ RAND
1 ASD (ASRNGW, Don Lewis)	(Tech Lib)
2 AFSWC (Tech Info Div)	3 Army Materiel Command
1 AFCRL (CRQST-2)	Rsch Directorate (MCR)
1 AFOSR	2 Picatinny Arsenal
1 AFOSR (SRHP, Dr M M Slawsky)	(SMUPA-DW6)
1 AFOSR (SRHP, Dr J F Masi)	1 Aberdeen Proving Ground
1 AFOSR (Dr A G Horney)	(Dr Eichelberger)
1 AFOSR (SRHP, Dr R Reed)	1 Aberdeen Proving Ground
1 AFOSR (Dr M A Cook)	(J Kineke)
1 OOAMA (OOYD)	1 Aberdeen Proving Ground
1 NASA	(F E Allison)
1 NASA (Ofc of Adv Rsch)	1 Redstone Scientific Info Ctr
2 NASA (Tech Lib)	1 Frankford Arsenal (Lib)
1 NASA, Rsch Ctr (W H Kinard)	1 Frankford (Pitman-Dunn Lab)
1 NASA, Rsch Ctr (J Stack)	2 Springfield Armory
4 NASA, Ames Rsch Ctr (Tech Lib)	(R&D Div)
1 Marshall Space Flight Center	2 Watervliet Arsenal
(W D Murphree)	(Col C A Conlon)
1 Marshall Space Flight Center	2 Watertown Arsenal
Adv Rsch Proj Lab (Dr W Johnson)	1 Rock Island Arsenal
1 Adv Rsch Proj Agency (Dr C Bates)	1 Army Engr Rsch and Dev Lab
1 Dir of Def Rsch & Engr (Tech Lib)	(Tech Doc Ctr)
2 Dir of Def Rsch & Engr (Dr R M Yates)	1 Dir of Spec Wpns Div
2 ARO (Scientific Info Br)	(C. I. Peterson)
1 Armour Rsch Foundation	1 Army Rsch Ofc - Durham
(Mr G H Strohmeir)	(Dr A S Galbraith)
1 Aberdeen Proving Ground	4 Bureau of Naval Weapons
(Tech Lib)	(R-12)
1 White Sands Missile Range	4 Bureau of Naval Weapons (RM)

1 US Naval Rsch Lab (Code 130/Mr WW Atkins)	1 Douglas Aircraft (Astropower Div)
2 US Naval Ord Test Stn (Mr L Cosner)	1 Intermountain Research and Engineering Co
2 US Naval Ord Test Stn (Tech Lib)	1 Air University Library
2 US Naval Ord Lab (Tech Lib)	1 U.S.Army, Edgewood Arsenal (Operations Research Gp)
2 US Naval Wpns Lab (Tech Lib)	1 US Naval Weapons Evaluation Facility (WEVS-1)
1 US Naval Wpns Lab (Dr Soper)	1 Wright-Patterson AFB, Ohio (SEPRR)
1 AFMTC (MTBAT)	
4 TAC (DORQ)	
2 Hayes International Corporation	
2 General Electric Company	
APGC	
1 PGLM	
4 PGBAP-1	
3 PGEH	
1 PGOW	
RTD Det 4	
2 ATWR	
1 ATWW	
1 ATTR	
1 ATB	
20 ATBT	

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Hayes International Corporation Birmingham, Alabama		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
		2b. GROUP N/A
3. REPORT TITLE THEORETICAL AND EXPERIMENTAL STUDY OF DETONATION WAVE REINFORCEMENT AND SHAPING TECHNIQUES		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report (1 May 1963 - 31 August 1964)		
5. AUTHOR(S) (Last name, first name, initial) Anonymous		
6. REPORT DATE December 1964	7a. TOTAL NO. OF PAGES 34	7b. NO. OF REFS 4
8a. CONTRACT OR GRANT NO. AF 08(635)-3624	9a. ORIGINATOR'S REPORT NUMBER(S) Engineering Report No. 1055	
b. PROJECT NO. 5841		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ATL-TR-64-80	
d.		
10. AVAILABILITY/LIMITATION NOTICES Qualified requesters may obtain copies of the report from DDC.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Ballistics Division Det 4, RTD (ATB) Eglin AFB, Fla	
13. ABSTRACT A study has been performed to determine the design criteria for a shaped charge and the associated liner geometry, employing wave shaping techniques. Heretofore, shaped charge jets have been characterized by a velocity gradient along the jet. The objective of this study was to design a shaped charge which would produce a jet characterized by uniform velocity. Such a jet would be projected downrange essentially as a single particle rather than a spray of fine particles. Parametric equations for a wave shaping lens were solved by an internally programmed digital computer. The proposed shaped charge design, featuring a cylindrical, metallic liner and a wave shaping lens of Polypropylene Plastic, was fabricated and test firings were accomplished.		

DD FORM 1473
1 JAN 64

UNCLASSIFIED

Security Classification

14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
Hype velocity Shaped Charge							

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. **GROUP:** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedure, i.e., enter the number of pages containing information.

7b. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8a. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTES:** Enter any limitations on further dissemination of the report, other than those

imposed by security classification, using standard statements such as:

- (1) "Qualified requesters may obtain copies of this report from DDC."
- (2) "Foreign announcement and dissemination of this report by DDC is not authorized."
- (3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through _____."
- (4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through _____."
- (5) "All distribution of this report is controlled. Qualified DDC users shall request through _____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.